Gunshot Location Systems

The transfer of the sniper detection technology from military to civilian applications

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***Abstract*—Since its first appearance by mid-nineties, gunshot location systems have become a valuable tool for acoustics surveillance against the illegal use of firearms in high crime urban areas. Sometimes criticized, the use of this technology is however spreading to more countries due its capability to provide not only gunshot related real time information, but also situational awareness and criminalistics evidence. This paper reviews the development of gunshot location technology, starting from its origin as a military solution for counter sniper operations, up to current days of intelligence led policing and of marketing strategies based on service demand. Acoustical emissions from gunfire events and its influence in shooter localization performance are analyzed. Fundamentals of gunshot origin estimation from muzzle blast wave analysis, and of trajectory estimation of supersonic projectiles from ballistic shock wave analysis, are overviewed. Gunshot location systems are furthermore described in terms of acoustical sensors architectures and its impact in the gunshot location result. Pros and cons of different approaches to data transmission, from wired to wireless, are discussed. Finally, the current status of research, development and implementation of this technology in the Latin America region are presented.**

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I. Historical Development of the Gunshot Location Technology

First attempts of locating the origin of artillery fire and of tracking bullet in flight were performed by Reid at Naval Surface Weapons Center in 1975 [1], and by Fischer, Loges and Meuser in 1984 who used a cruciform array of microphones to estimate the direction of arrival of gunfire acoustical wave fronts [2]. However it was in 1992 when Lahr and Fischer at the United States Geological Survey in Menlo Park, motivated by the high level of gunfire related crime in the city, demonstrates the feasibility of locate high intensity impulsive sound source in an urban terrain using acoustics sensors and seismic techniques and software. The system was composed of 5 wireless dynamic microphones distributed over an area of 0.84 x 0.28 kilometers and connected to a computer for seismic signal processing [3]. Besides of their promising localization results, the technique failed in discriminating gunshots from other high level impulsive sounds like door slams or cars backfires. Few years later, and motivated by sniper fire events in the Bosnian War the U.S. Army began a joint research program in gunshot and sniper localization together with the Defense Advanced Research Projects Agency (DARPA) and several defense related industries. One of the technological approaches developed as part of this research was a gunfire location system capable to be deployed in an urban warfare scenario. The System for the Effective Control of Urban Environment Security (SECURES) developed by Alliant Techsystems Inc., and installed by the first time at the Fort Benning onbase Olympic Village in the Olympic Games of Atlanta 1996, constitutes the first modern gunshot location system [4].

A. The Origins: Rising of Sniper Detection Technology

In spite of previous development attempts, modern gunshot location technology was the result of technological transference of a military application denominated Sniper Detection System first developed for counter sniper operations in the battlefield. During 1992 and 1995, Socialist Republic of Bosnia and Herzegovina breaks out into civil war, in which Bosnian Serb paramilitaries faced against government armed forces attempting to create a separate republic. This conflict is recognized as the most violent in Europe after World War II, and perhaps one of its most significant events was the siege of capital city Sarajevo by the paramilitaries.

The siege starts in May 2nd, 1992, and extends over three and a half years, being the largest in the modern warfare history. During the block, the Bosnain Serb haves soldiers located in the hills surrounding the city and equipped with many different types of artillery and heavy machine guns aimed at population areas. The Bosnia and Herzegovina government defense forces inside the city, although larger in number of troops, were unable to break the siege due the blockade of the city.

Among the armaments employed by the paramilitaries, the use of sniper weapons acquired fatal relevance. Infamous were the “Sniper Alley” events in which Bosnian Serb snipers located in the hills deliberately fired against civilians passing by across the main boulevard of the city. According to literature the paramilitaries snipers wounded 1030 people and killed 225 including 60 children [5]. Given these and others crimes against civilians, in 1994 NATO decide to intervene Bosnian War, of particular interest for this review are the pace keeping operations by the United Nations Protection Force and the introduction of the sniper detection technology for monitoring ceasefire agreements and for counter sniper operations.

Originally supplied by Roke Manor Research and BAE Systems to the British Army in 1994 for its use in the Bosnian conflict, appears the Hostile Artillery LOcator (HALO). The system was intended for computing the position of guns, mortars and shell bursts on the battlefield, and used as a system for collecting acoustic signals from many types of sources to obtain a picture of the battlefield in the acoustic domain. The performance of the HALO was based on fluid dynamics modeling and acoustic sensing technology and considers the deployment of small clusters of microphones [6].

Later, Metravib in France will introduces PILAR a counter sniper system provided to support French army operations in the Bosnian conflict. This was a portable system capable to collect data from the sound of both the muzzle blast and the ballistic shockwave of the gunfire. Gunfire localization was computed from the supersonic signature of the passing bullet. As result, the azimuth, elevation, range and bullet trajectory of the incoming gunfire were obtained [7].

At the other side of the Atlantic, the Joint Counter Sniper Program was initiated as an U. S. Army project in 1993 and by the middle of 1994 a draft requirement was formulated and some prototype technologies were demonstrated at Fort Benning and at Aberdeen Proving Grounds. Later in 1995 significant advancements over the state of the art in sniper detection technology were promoted by the DARPA. In a transcendental initiative, six important defense technology companies were sponsored to develop sniper detection prototypes of various kinds. According to DARPA specifications, the output of these systems should be an estimate of the shooter's location and a classification estimate of the caliber of the weapons. In 1997, the final field tests were completed at USMC Base Camp Pendleton, Military Operations Urban Training facility [8]. The tests were designed to provide challenging gunfire related scenarios with significant reverberation and acoustic multi-path conditions. Special shot geometries and false alarms were included to probe potential system vulnerabilities and to determine the performance and robustness of the systems.

The DARPA initiative leads to the introduction of a variety of new technological approaches to sniper detection and localization, including: sniper localization based on infrared emissions from the gun muzzle flashes, in the Fast InfraRed Sniper Tracker developed by Thermo Trex Corporation; the integration of acoustic and uncooled infrared sensing technologies in the Integrated Sniper Location System developed by SenTech, Inc. and Lockheed Martin [9, 10]; but also introduced significant improvements to the acoustic sensing technologies, including: the Sentinel developed by Science Applications International Corporation, which used 16 acoustic sensors and high resolution digitization of analog signals to perform ballistic shockwave analysis and robust determinations of azimuth, range, bullet trajectory, weapon caliber, and muzzle velocity [11]; the Bullet Ears counter sniper system [12] introduced by BBN Technologies of Massachusetts whose algorithm is regarded as the state of the art in sniper detection and is the most used by USA Army; and the previously mentioned SECURES/TAGIT-CS system developed by Alliant Techsystems Inc/Planning Systems Inc [13].

B. Present Days of Gunshot Location Technology

After the successful results of SECURES in Fort Benning onbase Olympic Village during the Olympic Games of Atlanta 1996, the system was also implemented in Dallas. At nearly the same time, another gunshot location system named ShotSpotter manufactured by Trilon Technologies, using a slightly different technology, entered the market by a system installed in Redwood City. Then, a research funded by National Institute of Justice and conducted by the Center for Criminal Justice Research at the University of Cincinnati evaluated the performance of the two installations at Dallas and Redwood City, revealing the potentialities of the technology against both gun related crime and random gunfire [14].

Between 1996 and 2009, SECURES was installed in several cities around the U.S. including Austin in Texas, Hampton and Newport News in Virginia, Prince George's County in Maryland, East Orange in New Jersey and the Johns Hopkins University Campus in Baltimore and Chicago. Regarding ShotSpotter, by 2009 about 35 cities in the U.S. haves been adopted this technology against gun related crime, including Saginaw in Michigan, Gary in Indiana, Seattle, Chicago, Rochester in New York, Minneapolis, Los Angeles County and Oakland, among others. But in 2009 ShotSpotter, Inc. acquires SECURES product line from QinetiQ, becoming the only dominator of market. At the beginning of 2012, sixty four cities in the United States and others in Canada, Puerto Rico, and Brazil had installed Shotspotter system for wide area acoustic surveillance.

II. PHYSICS OF GUNFIRE

A. Acoustical emissions of small arm fire

In physical terms, a fire comprises two main phenomena: a shock-induced chemical reaction of the ammunition propellant inside the gun barrel, and the dynamics of a small projectile released into air from the open end of the barrel. The shock-induced chemical reaction of the ammunition propellant derives in a two phase explosion. The first phase correspond to the ignition of bullet propellant and the subsequent turbulent flow of heat through the gun barrel, and the second phase represents the re-ignition of unburned propellant and combustion products in the air just outside the muzzle. On the other hand, the dynamics of the projectile constitutes a six degree of freedom movement influenced by the gravity force and by aerodynamic forces and momentums. It starts with the acceleration and spin of the bullet inside the gun barrel, follows with the release of the projectile into air from the open end of the barrel, continues with the flight dynamics of the projectile along its trajectory across the air, and finishes when the projectile reaches the target.

Most important fluid dynamics process related to the shock-induced chemical reaction is the muzzle blast flow of the exuding plasma from the open end of the barrel. This sudden exit of high pressure and high temperature plasma originates a muzzle blast wave which diverges spherically from the weapon muzzle [15~18]. Regarding the projectile dynamics, there are three important fluid dynamics phenomena. First, the piston-like action of the projectile nose releasing the muzzle induces a

shock wave process [19]. Second, the vortex shedding by the projectile in flight originates a trace of turbulence along the trajectory, which would eventually originate Aeolian tones as described by Sondhauss in early 1854 when [20-22]. Third, if the projectile velocity is transonic or higher it will produce a ballistic shock wave, or Mach cone, trailing the bullet in flight, whose pressure amplitude haves an N-wave shaped profile.

B. Acoustical Signature of Gunshot

Since the nineteenth century, the previously mentioned fluid dynamic phenomena have been observed using a photographic technique called shadowgraphy, or Schlieren photograph, as showed in figures 1 and 2. Shadowgrams and external ballistics have been closely related since Mach and Salcher first photographed shock waves produced by a bullet in 1887.

The sequence of images in figure 1 corresponds to consecutive shadowgraphs of the firing of a Pennsylvania State Police Beretta Model 96D. This weapon uses calibre 40 ammunitions, and the muzzle velocity is transonic. In this case the reader can observe the release of the muzzle blast flow from the open end of the barrel and its associated muzzle blast wave diverging spherically. By contrast, figure 2 shows a Smith & Wesson Calibre .44 Magnum revolver. In this case, a blast wave emanates from the rear of the weapon before the muzzle blast wave leaves the barrel. This two blast signature has been used for discriminating pistols from revolvers. In both cases the projectile velocity is either transonic or subsonic, in this way no ballistic appears in the signature.

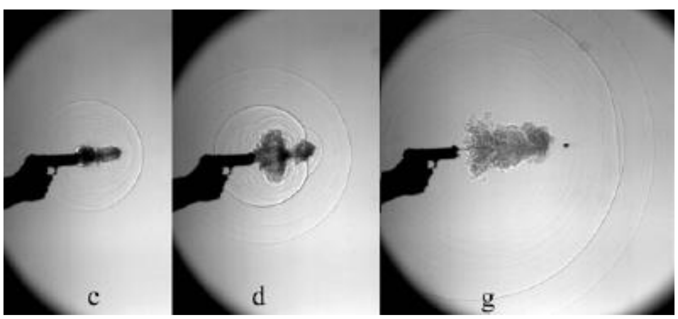

Fig. 2.10. The firing of a Beretta 96D pistol (muzzle velocity 440ms-1) [adapted from 23].

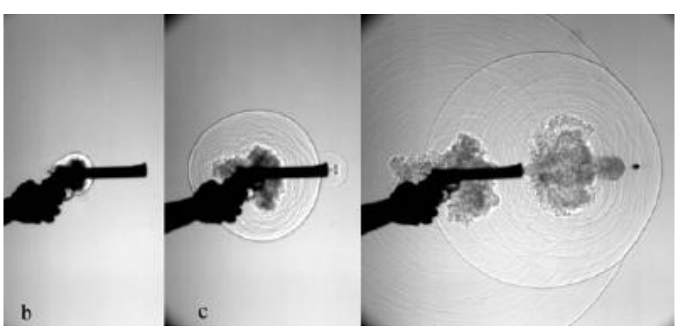

Fig. 2.12. Smith & Wesson Calibre .44 Magnum revolver [adapted from 23].

III. GUNSHOT LOCATION SYSTEMS

In the context of ISTAR, a system of acoustical sensors is a high technology instrument capable to perform surveillance and target acquisition tasks. Surveillance is thought as the activities and means used to make observations of acoustical components of environmental noise in a systematic and continuous way, day and night, in all weather condition. Target acquisition, on the other hand, concerns to characterize acoustical sources that compose environmental noise by executing detection, spatial localization, reconnaissance and identification of one or more previously specified targets. A particular class of systems of acoustical sensors are those devised to detect, locate, and identify gunfire or shooting noise in an urban environment, generically termed as Gunshot Location Systems. The system operates by processing the information contained in the acoustical emissions of the gunfire event to obtain estimations of the spatial coordinates – azimuth, elevation, range – of the gunfire origin, as well as other ballistic features of interest. In this application gunshot localization result is displayed within a few seconds after a shot by means of a user interface and usually integrated into a geographical information system.

A. Electro-Acoustics Sensors Architectures

Sensors architecture consists of a network of electroacoustics sensors distributed inside the area under surveillance. The sensors nodes are located mainly at street intersections and at high places, for example at cellular telephony antennas, lighting poles or high buildings. The sensor itself usually consists of a low cost condenser type acoustic transducer sensitive to acoustic pressure and having omnidirectional pickup pattern.

Microphone data transmission from the sensor nodes to the CPU has been done using two different approaches. The first corresponds to wireless transmission channels in the SECURES system using 500mW RF transmitters and receivers at 900 MHz. In the second approach, dedicated telephone lines are used as data transmission channels, this method is employed by Shotspotter. While the use of telephone lines shows to be more robust and less sensitive to EMI, RF transmission technoligy is associated to lower cost of operation.

Coverage of acoustic sensor network varies from one implementation to another, and depends of acoustic sensor sensitivity to pick up muzzle blast wave form and on acoustics environment. In open air conditions and in absence of background noise, a small arm fire muzzle blast wave can be perceived up to 600 or more meters from the shooter. However in an urban environment, acoustic multipath introduced by buildings and higher levels of background noise could drastically degrade de quality of propagating acoustic signals. Currently, the number of acoustic sensors per square kilometer can vary from about 20 to about 5 sensors per square kilometer.

B. Acoustical Signature Analysis for Gunshot Location

It has been previously established that the acoustical signature of a fire event comprises a muzzle blast wave

diverging spherically from the weapon's muzzle, and a N-wave shaped ballistic shock wave emanating from the projectile in flight when its velocity is transonic or higher. Based on the observation and analysis of these phenomena, modern gunshot and sniper localization systems are capable to estimate azimuth and elevation to the shooter; range to the shooter; trajectory of the projectile; calibre of the projectile; and muzzle velocity.

In order to estimate the origin of a sniper fire event, acoustical signature analysis considers the detection of such a fire event, and the individualization and analysis of its acoustical components, i.e. muzzle blasts and ballistic shocks. Further, although muzzle blast and ballistic shock are mostly analysed in separated ways, some relations between them are also of importance.

1) Gunshot Detection: Gunshot detection is the first step of any gunshot localization system. It comprises distinguish the gunshot noise from the background noise, and discriminating the gunshot noise from other similar sounds, such as hammer strikes, exploding balloons, or cars backfires. Further, discrimination of gunshot direct sound from ground reflections or multipath distortion is important in urban gunshot localization.

Basically, the event of distinguish a fire event from the background noise is performed observing the amplitude of the sensors signals. A possible gunshot is detected when the amplitude of the signal exceeds a determined threshold. Either the instantaneous amplitude or the signal to noise ratio are used in this regard. The detection threshold may be fixed or variable and is determined by the background noise conditions. Moreover, once a possible gunshot has been detected, blast wave impulse duration is also used to discriminate gunshot noise from other high amplitude noise. A predicted gunshot event is expected to occur when the blast wave impulse duration is within a predetermined range, usually about 50 mSec [24]. Other approach for detecting the ballistic shocks over background noise using wavelet analysis has been tried by Sadler et al. [25] using quadratic spline functions, up to 8 levels of decomposition and cross scale analysis.

Furthermore, the abruptness, or sharpness, of a signal is also used to distinguish a gunshot noise from other impact or impulse sound [9]. The sharpness value at a given current point in the time series is the ratio of the maximum RMS within time interval after the current point to the maximum RMS of a time interval preceding the current point. The sharpness is converted to a decibel scale and compared with a threshold value. A running calculation of this value gives a sharpness profile in which gun fire noise stands out as a large peak.

When distributed sensors architectures are used, as in the case of urban gunshot location systems, directional characteristics of the propagating muzzle blast waves becomes relevant. First, the frequency content of muzzle blast waves has shown to be highly directive. Most of the low frequency content of the muzzle blast is radiated directly in front of the gun [26], and not to the sides or the rear of the gun. Second, gunshot acoustical signatures observed behind a fired gun displays a pattern of peaks or oscillations not appeared in the blast impulses recorded in front of the fired gun. These oscillations have been used to discriminate a gunshot from other impulsive sounds [13], and should be useful to distinguish between short and long barrel weapons [27].

The muzzle blast versus ballistic shock classification is performed in the frequency domain due to its different frequency content. Muzzle blast detection is done on band-pass filtered data that considers a high-pass cutoff frequency of 100 Hz and a low-pass cutoff frequency of 500 Hz. On the other hand, ballistic shock wave detection uses high pass filtered at a cutoff frequency of 700 Hz to remove any low frequency noise and DC bias but maintaining, to some extent, the characteristic N-wave form. The classification is finally done by comparing the energy of the spectrum in the high frequency region to those in the low frequency band [28].

2) *Gunshot Origin Estimation*: Once the muzzle blast and ballistic shock have been detected and separated, times and directions of arrival of these two waves to the microphone arrays must be calculated [29]. Directions of arrival are inferred from the time delay of arrival of each perturbation to pair of transducers. Time delay of arrival measurement are typically performed calculating the cross correlation or the cross power spectrum between two microphone signals [30]. In addition, time delay estimations between pairs of microphones have been done using Bayesian estimation and using genetic algorithms. To avoid ambiguities in the direction of arrival estimates, at least two pairs of microphones are required for plane localization; consequently, three pairs will be required for 3-D localization. The range to the shooter is primarily estimated by determining the curvature of the muzzle blast wave front using microphone arrays and by means of an appropriate triangulation algorithm [31]. In addition, range can be estimated multiplying the muzzle blast time of arrival by the speed of sound. The muzzle blast time of arrival is calculated as the difference between the ballistic shock time of arrival and the observed time interval between the shock and the blast.

3) *Projectile caliber and trajectory estimation*: Projectile caliber is estimated by performing N-wave analysis. In this sense, empirical relationships between the slant range S, the N-wave peak amplitude, and the N-wave duration have shown to be useful for estimating both projectile caliber and ballistic coefficients. The slant range S corresponds to the distance over which the N-wave has propagated in air from the point it was radiated by the projectile in flight to the microphone.

Ballistic trajectory estimation of supersonic projectile using acoustical signatures is currently obtained relating the trajectory of the projectile to the arrival times of the ballistic shock wave at different transducers in a microphone array [11][28]. In state of the art system, measured and predicted values of shock arrival times and inter sensor time delays of arrival (produced by the passing shock across the microphones of the array) are compared into a cost function [28]. Further, cost function is expressed in terms of a set of unknown parameters to be found by minimizing such a function. These parameters correspond to the trajectory azimuth and elevation angles, the two coordinates of the trajectory intercept of a reference plane, and the bullet Mach number. For minimizing cost function, the Levenberg-Marquardt method of nonlinear

least squares is used. While measured shock arrival times are obtained using a microphone array and time delay estimation, predicted shock arrival times are obtained using a shock wave time of arrival model which considers a ballistic model and aerodynamic drag force [28]. This ballistic trajectory estimation algorithm is regarded as the state-of-the-art in sniper localization.

In the last time, other approach in which a complete N wave form propagation model, including N-wave amplitude, duration and rise time, and not only a time of arrival model, is proposed for more accurate and robust slant range estimations [32].

IV. Performance, Benefits and Disadvantages, and Marketing Strategies

A. Perfonmance Benchmarks

According to performance data provided by manufacturers and research studies, gunshot location systems are capable to detect and locate appropriately more than 80% of gunshots event, but this quantity could be reduce significantly by effect of electromagnetic interference and other environmental acoustics issues. Accuracy of the gunshot location estimates is about 2.5 to 5 meters.

B. Benefits

In the present days of Intelligence-Led Policing, which promotes the use of technology capable to provide intelligence information and evidence, gunshot location technology takes advantage of its unique attributes.

According to manufacturers, performance result has demonstrated the effectiveness of the technology in reducing gun related crime. Reductions of about 30% in the number of gun-related crime, and in more than 70% the number of gunfire in public space are usually reported after implementing the systems. Gunshot location technology also reveals the hidden data of not reported fire events. According to collected data, only the 10% of gunshot are reported to police.

Perhaps one of the most interesting benefits of this technology corresponds to its ability to record and store gunshot audio data. There are several examples in which the use of gunshot location and audio registers has served as criminal evidence.

Integration of gunshot location system in the urban design of high crime urban areas brings another important attribute of the gunshot location technology which is its capability to provide situational awareness of public spaces were installed. This is beneficial not only to prevent gun related crime, but also to reduce random or celebration gunfire. There is also some evidence that public awareness of the gunshot location system may serve to decrease gunshot-related emergency calls.

C. Disadvantages

Perhaps one of the most controversial aspects of the gunshot location technology is noticed in the performance evaluations of SECURES and ShotSpotter sponsored by the National Institute of Justice []. According to these studies the technology is not able to produce a real gun related crime reduction. However these investigations were performed over limited period of time of less than a year and with one of the systems reporting interference related failures. There are no reports about longer time performance evaluations published yet.

Among other disadvantages of implementing gunshot location technology noticed by some researches we encounter the increase in work load for police officers who must attend a larger number of reports related to gunshots.

An important issue of the current gunshot location technology is the data transmission technology employed to send the microphone data to CPU, which in the case of RF transmitters could be very susceptible to interference.

D. Gunshot Location Market

Gunshot location systems haves a cost of about USD $60.000 per square kilometer or its equivalent USD $8.000 per sensor node. The marketing model has evolved from begin selling stand-alone systems to police and public security related agencies, to provide contracts of gunshot location based on service demand.

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